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INFLATABLE CONCENTRATORS FOR SOLAR THERMAL PROULSION

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Abstract

development of Solar Powered Rocket Engine systems :nds heavily on demonstrating the technology for light- ;ht space-deployable solar concentrators. Large inflat- parabolic shaped thin film reflectors can be packaged ı other solar-powered propulsion elements and de- 'ed. The solar rocket can be used to efficiently transfer .oads from Low Earth Orbit (LEO) to Geostationary it (GEO). Thin film casting and reflective coating niques for fabricating the thin film concentrators have ı demonstrated by casting large 5 meter diameter thin . polyimides. These processes use newly developed /imide materials supplied by NASA Langley Research .ter (LaRC).

'his paper will summarize continuing research to de-)p a collector design and manufacturing methods to :icate parabolic thin film concentrators. The research included design refinement of the conventional torus ported membrane. The refined collector design also .udes a secondary concentrator that improves the per- nance of the optical system. Reflector fabrication tech- ues have been developed and demonstrated which can :xpanded to construct and evaluate the refined collector ign.

Introduction

›viding lightweight, highly accurate reflectors for space)lications has been a goal of researchers for many years. in film reflecting material fabricated to a precise curva- e has the advantages in the areas of weight, cost, and :kaging. Lightweight large reflectors have many current :l future space-related applications. Solar thermal pro- lsion, solar dynamic power systems, lunar soil process- ;, and large RF and microwave antennas are good ex- ıples. The use of newly-developed thin film polyimides fabricate large reflectors can be applied to meet the needs the space-related applications.

A solar thermal propulsion system with inflatable solar concentrators was originally described by Ehricke in 1956 (ref. 1). This concept was further defined by Electro-Optical Systems, Inc. (ref. 2) during the 1960's and by Rockwell International (ref. 3) in 1979. The Solar Powered Rocket Engine is expected to produce specific impulses of 900 to 1200 seconds. This is over two to three times that of conventional liquid hydrogen/oxygen engines. This performance would significantly improve travel from low earth orbit to geostationary earth orbit and other planets.

The solar thermal rocket offers the optimum propulsion means for LEO to GEO transfer vehicles, provided that specific impulse (I_{sp}) on the order of 1,000 seconds at moderate thrust levels can be achieved. These I_{sp} and thrust levels are contingent on the availability of large lightweight auto-deployable solar concentrators of a total concentration ratio on the order of 10,000:1. Fabricating the concentrator membrane of the optically-required configuration is a major challenge. Conventional methods of fabricating the concentrator from sections produces disruptions in the reflector surface along the seamed surface. Also, concepts which use an outer torus support structure design have difficultly in terms of maintaining in-plane shape, because of the film tension and structure interface loads. These loads must be properly distributed in order to avoid distortions and gross optical errors in the primary concentrator. Packaging and deployment of a concentrator with a torus support also has design problems. These concerns led to the design of an inflatable concept which eliminates the need for the torus.

Concentrator Designs

The solar thermal propulsion concept (STPC) requires the use of two large, highly accurate inflatable concentrators. The shape of the original collector design from Ehricke was spherical. The concept shown in ***Figure 1*** depicts one of the inflated spherical collectors. In this design, one-half of the spherical collector is reflective coated and the other half a transparent canopy. Incident solar energy passes through

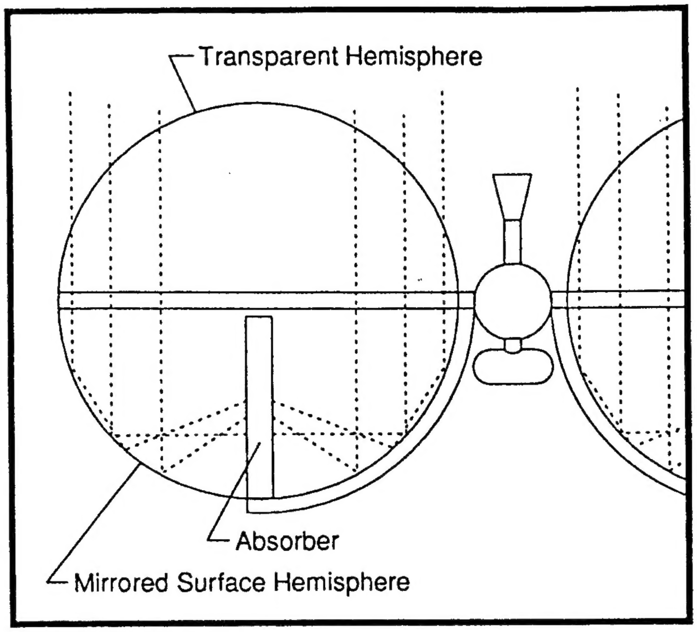


Figure 1 Kraft Ehricke's Inflatable Concentrator Concept

the transparent canopy and is reflected from the back of the collector to the absorber. The absorber for this design is located inside the spherical reflector. Additional studies improved the Ehricke design with regard to locating the absorber outside of the inflated collector. These studies resulted in an off-axis paraboloid concentrator design with the absorber located between the two collectors. This design enables solar pointing and guidance and control in addition to removing the collectors from the solar rocket exhaust plume. The concentrators in the refined designs are portions of a large paraboloid of revolution about the solar rocket vehicle. The shape of the concentrators is an off-axis, clam-shell-like shape. The feasibility of STPC depends on the design of a concentrator and development of methods to fabricate, package, and deploy the concentrators.

Torus Supported Concentrator

The torus support concentrator design is shown in ***Figure 2***. The design consists of a transparent canopy, reflective membrane, and elliptical support torus. The success of this design is dependent upon constructing a deployable support torus. The requirements of the support torus are that it must be planar and accept film tension and support structure loads of the solar rocket. If the support torus distorts, the distortions will propagate across the concentrator causing optical errors. The torus also must be packaged efficiently and follow the deployment paths of the concentrator, canopy, and support structure.

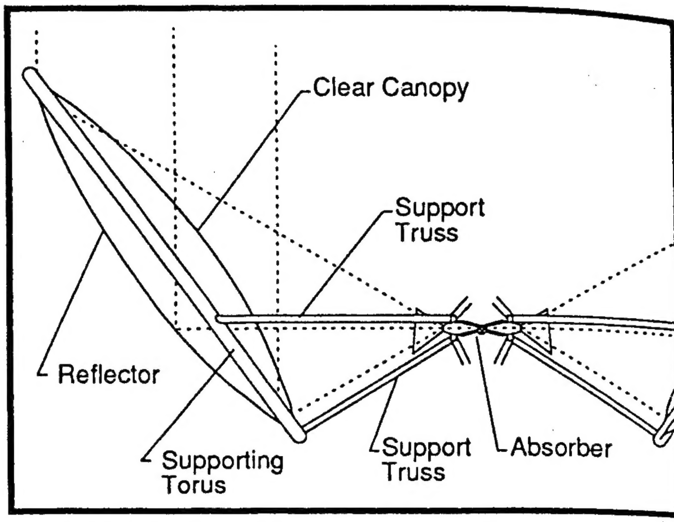


Figure 2 Torus Supported Inflatable Concentrator Concept

Several methods have been researched to fabricate the elliptical torus. The torus supported configuration involves very complex forces-and-deflections relationships between torus and concentrator. These conditions are difficult to model analytically or refine empirically. The analysis becomes more complicated for the off-axis configuration than for a symmetrical concentrator. If a single inflation pressure is used, the torus must be very large to achieve force-balance with the concentrator. If a torus of reasonable size is used, a much higher inflation pressure is required than that used in the concentrator/canopy chamber. Deployment of the torus design concentrator can become a difficult task when fully integrating the support structure and concentrator. Specific deployment steps and paths are required for successful deployment of the concentrator system. It is also a difficult problem to design a technique for joining and transmitting the operating load distribution between the torus and the periphery of the concentrator. Improper joining can cause optically significant distortions that propagate over large regions of the concentrator.

Single Chamber Concentrator

Design problems with the outer torus support led to the investigation of an alternative concept that does not have a torus. The concept is shown in ***Figure 3***. In this design, the two-chamber concentrator plus support torus of the classical design is replaced with a single chamber configuration. An inflatable thin film off-axis paraboloidal concentrator of a single chamber design can provide high concentration ratios, ease of deployment, and increased reliability. The bulbous shape of the concentrator also increases the rigid-

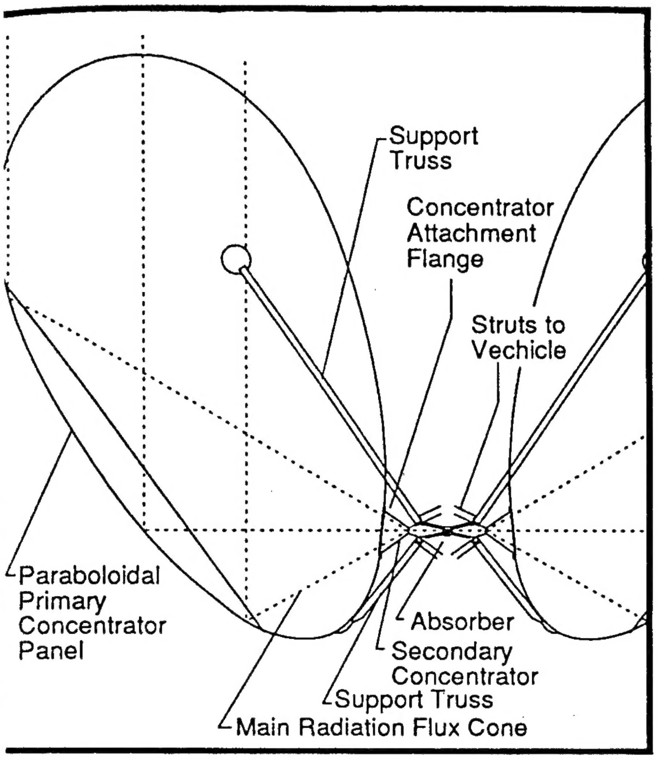
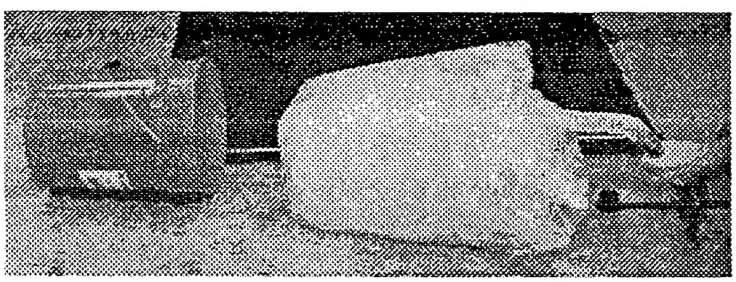


Figure 3 The Single Chamber Inflatable Concentrator Concept

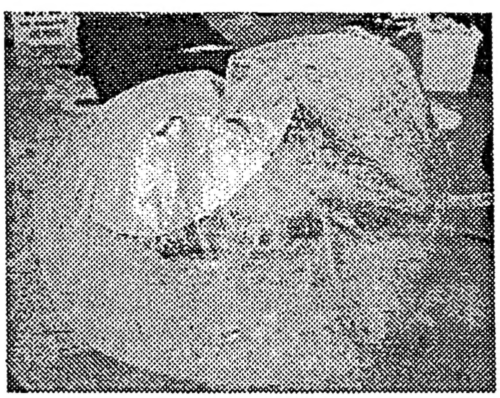
ity/moment-of-inertia of the collector. The rigidity is required for good optical performance. The single chamber design allows for structural attachment to the solar propulsion vehicle similar to the torus supported design. The single chamber has a lower number of components, requires only a single inflation pressure, and is more reliable to deploy than the torus supported design. The design concept is based on the fact that the skin stress distribution in a thin walled pressure vessel can be modified by appropriate geometric design. The single chamber design inherently involves a nearly-perpendicular incidence angle of incoming light striking the transparent canopy. This results in minimal Fresnel Law reflection losses from the canopy.

A feasibility model was constructed to verify the concept of the single chamber design. Deployment of the model is shown in ***Figure 4***. The design enables 1-G ground testing of the concentrator. Ground testing can include packaging and deployment verification and operational testing. The deployment of the design consists of a single inflation pressure applied in the chamber. Optimization of the shape of the single chamber will be done to reduce the total size of the chamber. The shape refinement will be done iteratively by re-shaping the casting mandrel. Eventually analytical techniques will be incorporated to improve the prediction of the optimum single chamber shapes.



Secondary Concentrators

The practical difficulty of achieving simultaneously the optical accuracy requirements, weight, stowed volume, and autodeployment requirements for all the primary concentrator concepts considered is severe.



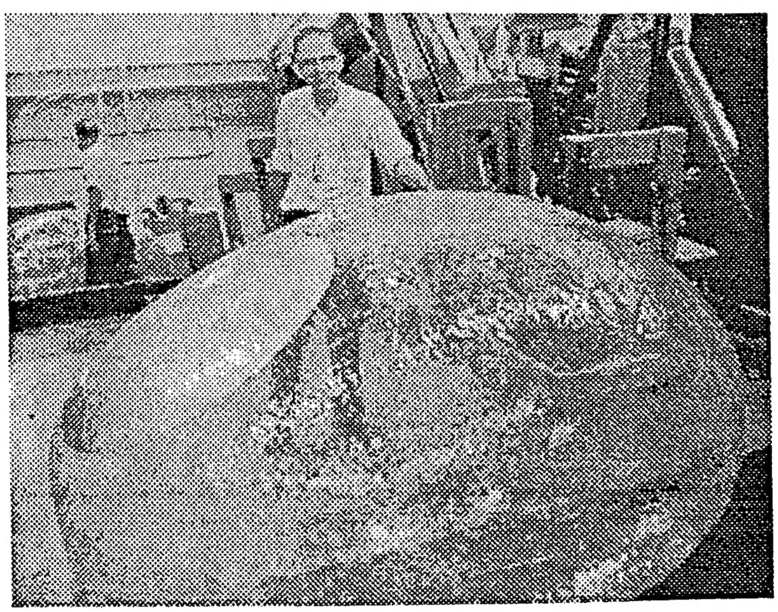


Figure 4 Deployment of the Phase I Feasibility Model — showing model ejected from the cannister, with inflation near completion and with inflation complete, showing the position of the primary concentrator panel.

Neither weight nor concentration ratio can be compromised without destroying the performance of the solar rocket. A related element in the solar propulsion design is the use of a reflective secondary concentrator. A secondary concentrator can simultaneously increase the total system concentration ratio, in turn reducing the primary concentrator requirements. A secondary concentrator can also reduce the thruster input energy drop-off caused by small pointing errors of the system and serve as a radiation shield. The radiation shield can protect the critical concentrator support structure main pivot and strut hub area from exposure to the concentrator focused output beam in the event of moderate-magnitude pointing errors.

In the case of the single chamber concentrator concept, the secondary concentrator also serves to extend the distance of the primary concentrator from the output focal plane. This is required for adequate clearance between the thruster plume and the bulbous front surface of the concentrator assembly. The secondary concentrator also serves as a key part of the main support structure linking the concentrator main pivot assembly of the solar rocket.

A point should be made regarding the design of a secondary concentrator for the solar rocket. The conditions for re-radiation of energy by the absorber become decisively important when the peak temperature of the absorber is critical, rather than merely incident energy flux. An appropriate parameter of the concentrator/absorber system is the concentration ratio divided by the re-radiation view angle. An example of the importance of this parameter is the fact that an improperly designed secondary concentrator may increase the system concentration ratio, but also may increase the incoming beam cone angle. The increase in beam angle will increase the absorber re-radiation view angle resulting in a drop in absorber temperature. This drop in temperature would reduce the performance of the solar rocket. A properly designed secondary concentrator can increase the performance of the total optics reducing the requirements of the primary concentrator.

Reflector Fabrication Methods

Ideally a thin film concentrator would be constructed to a desired shape without any seams or discontinuities. Large thin film reflectors constructed from flat stock material require seaming because film materials are typically only available in widths less than 2 meters. Any double curving of the stock film must be achieved by processing, such as relaxation forming. Gores, flat or doubly curved, must then be assembled to form a large area reflector. Assembly control of all the stresses at the seam is difficult. Even if a completely stress-free, wrinkle-free, seam is achieved, the reflector is no longer homogeneous across the surface. When a stabilizing force is applied to hold or further shape the reflector, this non-homogenity tends to result in scallops across the reflector, a major source of figure error. For this reason, alternative reflector fabrication methods using spin and spray cast polyimides were developed.

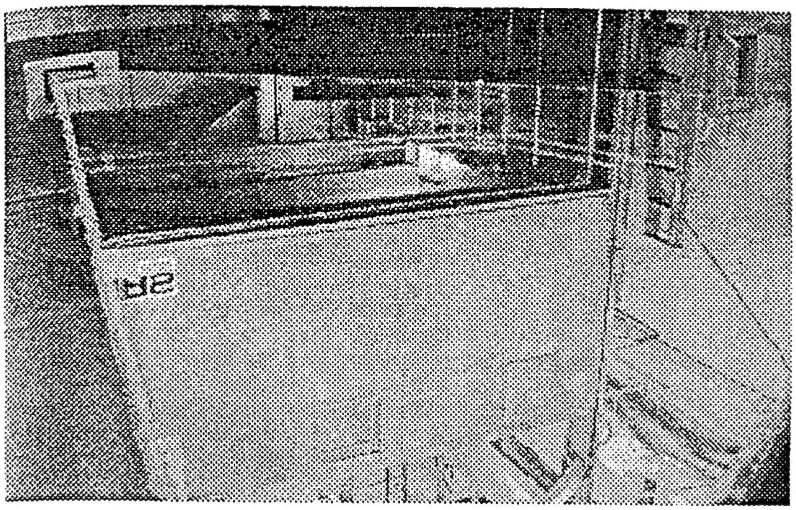
Reflector Materials

Commercially available polymer films have directional anisotropic properties, small widths; they are also flat, and susceptible to atomic oxygen, and UV degradation. The disadvantages of "off-the-shelf" polymer films led to investigating and developing techniques for constructing reflectors using polymer films developed by NASA Langley Research Center (LaRC). These polyimides have been developed for space applications. The family of materials developed by LaRC include both heat imidized and chemically imidized polyimide films (ref. 4). The chemically imidized is reversible; it can be redissolved and used again. Further, since the materials may be obtained in solution and then cured, doubly curved membranes can be produced. Spin and spray casting techniques have been used to manufacture films in the laboratory.

A LaRC material currently used is powdered polyimide 6FDA+APB dissolved in Diglyme solvent. The film is chemically imidized and is cured at a temperature of 200°C. This film is reversible and can be redissolved with the solvent and reused. These improved polyimides are transparent and have improved atomic oxygen resistance. Typical properties which are critical when selecting materials for thin film concentrators are:

Mechanical properties
- Tensile strength
- Notch toughness or tear strength
- Resistance to creasing and folding stress
- Low temperature creep during prolonged compacted stowage
- Coefficient of Thermal Expansion (CTE)
- Density

Optical properties
- Spectral absorption/transmission
- Refractive index
- Surface specularity as substrate for reflective coatings



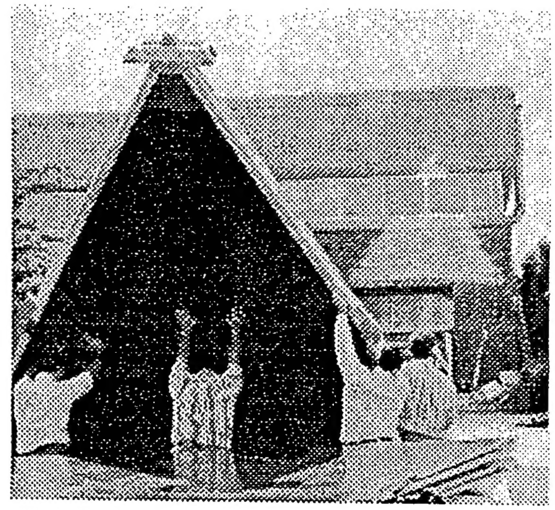


Figure 5 The large oven at SRS mirrored in the Reflective Coated Polyimide used on the Heliostats and a solar image reflected from the silvered polyimide membrane

Space environment endurance
- UV, atomic oxygen resistance
- Temperature range
- Vacuum compatibility
- Micrometeoroid abrasion
- Puncture response

Manufacturability
- Spray casting
- Atmosphere, humidity, temperature
- Adhesive bond compatibility
- Accept Metallization

Reflective and Protective Coatings

abricating collectors from solution polyimide requires ıat a reflective and protective coating must be applied to ıe film following the casting process. Methods used ɔmmercially to apply silver and aluminum coating are ɔuttering and vacuum evaporation. These processes re- uire vacuum chambers and related equipment. Electroless ɔray silvering has been demonstrated to give highly re- ective uniform coatings on large polyimide films. The lver has acceptable adhesion and compatibility with sili- ɔne protective overlayers. This method does not require ıe very large equipment investment required for vacuum ıetallization of large double curvature films. This process as been developed and demonstrated by silvering of the ırge films for the Solar Laboratory thin film heliostat. This evelopment has been a major milestone in establishing the :asibility of large thin film solar concentrators made from olyimide cast solutions. ***Figure 5*** depicts a section of the ıin film heliostat that was recently reflective coated. The :flective silver coating was applied by the wet chemical process. Continued development of the process is required for the optimization of process parameters. Improved development of the silvering process can provide maximum adhesion, reflectivity, uniformity, and compatibility with protective overlayers.

A protective overlayer for the reflective coating is also a critical factor. Silver requires protection from tarnishing agents in the atmosphere, and from atomic oxygen (AO) in space. The protective overlayer must be adherent, non-tarnishing, able to endure and screen out reliably the factors harmful to the silver. It must also be compatible with folding/stowage/deployment of the concentrator, and compatible with suitable deposition processes such as spraying. Silicone coatings have been used with success in related efforts. The silicone coatings are the leading candidates for protective overlayers.

Casting and Forming Hardware

The equipment required for the spin or spray casting and curing of the polyimide, which are presently available, are a spin table, clean room, and heat curing oven. The facility and equipment layout is shown in ***Figure 6***. Casting mandrels used are enclosed in a clean room to minimize dust particles that collect during the film casting process. The clean room incorporates a positive flow environment control method. The casting of the film requires low humidity which can be achieved with the ventilation system. A positive flow system keeps the concentrations of the evaporating fumes well below safety standards for the off-gassing of solvent fumes. The oven temperature can be

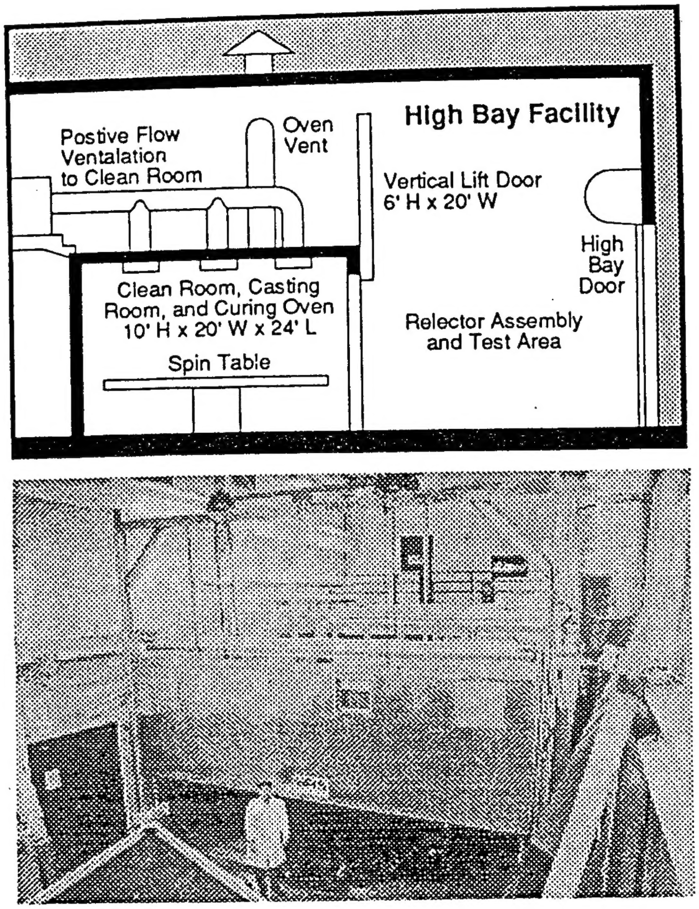


Figure 6 Simplified Diagram showing the general layout of the Clean Room, Casting Room, and Curing Oven at SRS; and a photograph of the High Bay.

controlled to 250°C. The oven includes a large door opening to allow for removal of the samples and mandrels.

Conclusion

Preliminary models of the single chamber concentrator have been fabricated. The concentrator models deployed properly and conformed to the desired shape. Fabrication procedures for spray casting polyimide and reflective coating large area films have been demonstrated. These processes will be used to fabricate larger test articles of the single chamber concentrator design. The test articles will be used for further refinement and demonstration of the single chamber design.

The advantages of spray casting thin film polyimide membranes as a one-piece unit without a torus eliminates the problems previously encountered with joining the membrane to the torus. This improves the success potential for developing and fabricating solar concentrators for the near term flight article test, and eventually, the orbital transfer vehicle.

Finally, degradation of polyimide concentrators exposed to the space environment has been a major concern for several years. Materials exposed in low earth orbit have degraded over time as a result of exposure to atomic oxygen (A0). Samples of the candidate LaRC polyimide materials are expected to be exposed to AO in a Space Shuttle experiment in June 1992. These samples will be fabricated under the conditions in which the large scale reflector will be made. Leading candidates for the test experiment are silicone coated, silvered polyimides and uncoated transparent polyimide. The shuttle experiment will expose selected materials to a 12-hour LEO space environment. This experiment will aid in the proper selection of materials for the inflatable concentrators.

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